July 26, 1999

Logistics SOFC Design and Other Parson Team Support Activities for DOE/FETC

J.H. Hirschenhofer and J.S. White – Parsons Corporation, Reading, PA
R. E. James – DOE Federal Energy Technology Center, Morgantown, WV

The Department of Energy's Federal Energy Technology Center (DOE/FETC) contracts the Parsons Corporation for advanced technology services. Tasks encompass support for a spectrum of advanced power generation technologies including fuel cells.

Elements of the fuel cell service task are broad, but, in essence, can be organized as:

- Process Engineering
- Virtual Design
- Cost Engineering
- Information and Training

Parsons has the flexibility to place subcontracts to comprehensively address issues covering these four elements. Presently, subcontracts are in effect with Michael A. Cobb and Company, Arthur D. Little, Inc., and Training Consultants, Inc. These subcontractors support cell/module design, cell/module cost estimates, and training. Parsons' internal scope is primarily in the areas of technical support, system analysis, and balance of plant design.

Representatives from the Parsons' team have been selected as participants on a DOE team along with Battelle Northwest Laboratory and members of the FETC staff to promote the development of advanced fuel cell concepts. The program is intended to assess results from to-date fuel cell development, then build innovative concepts that promise a step improvement in fuel cell performance and cost. This is a suitable role for government, to focus on long-range, high-risk approaches that promise to deliver extraordinarily high performance and low cost. This differs from fuel cell developers that pursue low-risk progress by fully developing existing cell designs and integrating them into systems with pragmatic balance-of-plant components.

The program team is evolving candidate fuel cell/module/system configurations. The first advanced concept candidate, based on solid oxide technology, assumes the role as a benchmark against which concepts championed by others can be measured. Once the most promising concept is identified, technology areas needed for development will be determined to establish a new, next generation fuel cell development program.

These are the specific activities that have been accomplished by the Parsons team members in support of the benchmark concept evolution.

Michael Cobb and Company is providing engineering development and design in concert with FETC to configure fuel cell candidates. There has been one SOFC advanced concept candidate identified to initiate system performance and cost analysis. The configuration is being evolved to produce even higher power density cell elements. The activity includes consideration of low cost processes to produce the single cell element, then building from the element through a series of steps to fuel cell modules that have a range of electric capacities.

Arthur D. Little (ADL) is performing reviews of the candidate cell elements-to-module designs. These reviews address material selection, fabrication processes, performance prediction, and cost estimating. Comments feed back into the design to improve the candidate approach. While FETC and Cobb are determining the cost of advanced tubular concepts, ADL is developing manufacturing costs for "typical" planar concepts. In parallel, Mark Williams and the FETC Fuel Cell Product Team are evolving formal technology transfer strategies study results as well as the skills for independently executing these kinds of studies. FETC believes the ability to do these kinds of engineering analyses must be more common.

Training Consultants assists in developing educational material to support the program. This includes assessing the audiences and their needs for courses, developing a training and information business plan on how to develop the necessary courses, developing material for a Fuel Cell Performance and Systems Course, outlining a Fuel Cell Theory and Systems Course, and assisting FETC with presentation preparation.

Parson's role in the program to-date has focused on system design activities. Parsons has provided verification of FETC conceptual level design of several power systems using the initial SOFC advanced concept candidate fuel cell module. FETC developed a comprehensive, system analysis computer model that is simple to operate by anyone versed in the use of the base, commercially available spreadsheet program. Besides use for in-house development, it is FETC's intention to make the systems analysis template available for training courses that provide understanding of the advanced fuel cell concepts.

Parsons verified the operation and results of the FETC spreadsheet analysis model by comparing state point information using the more sophisticated commercial flowsheet simulator ASPEN that requires dedicated analysts with special training. FETC and Parsons performed analyses for 4 MW class power plant cycles. These included a simple fuel cell cycle, a fuel cell/gas turbine combined cycle, and a fuel cell/steam turbine combined cycle. These cycles use natural gas fuel.

More extensively, Parsons determined the technical feasibility of using logistic fuels with the FETC advanced concept candidate. There are two logistic fuels of interest. The first, DF-2 or diesel fuel, is 13.2 weight percent hydrogen with a sulfur content of approximately 0.04 weight percent. The second, JP-8 or jet fuel, has hydrogen content of approximately 15 percent and a relatively lower sulfur content of 0.008 weight percent. There is plenty of supporting data that indicates the feasibility of processing liquid logistic fuels into gaseous fuel cell feeds. The main technical question is whether these front-end processing units can be feasibly incorporated with FETC's fuel cell concept. Parsons found that the logistic fuels-based power plant system with FETC's advanced concept candidate is thermodynamically feasible. Technical feasibility, however, is dependent upon completion of a study program to mature FETC's fuel cell concept plus address research and development issues.

A power cycle incorporating the FETC fuel cell candidate using a representative logistic fuel was developed at a conceptual level. This cycle has a representative state-of-the-art fuel processor configuration. Parallel efforts to develop an improved system configuration were also conducted by Parsons with FETC. The ASPEN model was used to generate a heat and material balance and to determine the system performance. A cell voltage of 0.79 was assumed. Net system efficiency was estimated to be 66.3 percent LHV. This efficiency value corresponds to a net power output of 3,335 kWe.

Figure 1 is a computer aided design drawing of the logistics plant and Figure 2 is the flowsheet diagram. A discussion on the cycle follows.

Fuel Conditioning

Liquid fuel supplied in stream F1 is pumped to high pressure (680 psia) and then heated to 382°C (720°F) in heat exchanger HX3. Heat duty is provided by cooling recycled fuel gas flowing from the exit of heat exchanger HX2. Hydrogen, in Stream H2, is concentrated in a PSA from recycled fuel gas and mixed with the diesel feedstock prior to entering Heat Exchanger HX3. The hot vapor stream from HX3 is routed to the hydrogenerator reactor. In the hydrogenerator, recycled hydrogen saturates the aromatic higher chain hydrocarbons and combines with sulfur to form H_2S. The saturated fuel gas stream is then routed to the sulfur guard. The sulfur guard is a vessel that contains a zinc oxide sorbent bed that chemically absorbs gaseous sulfur. The resultant fuel gas sulfur content is less than 1 ppmv.

Effluent from the zinc oxide guard bed in Stream F5 is de-pressurized with a throttle valve to 385 psia. The sulfur-free raw feedstock stream is heated to 482°C (900°F) in Heat Exchanger HX2 and sent to the adiabatic pre-reformer. Cooling recycled fuel gas from the pre-reformer in Stream S2 provides heat duty for Heat Exchanger HX2. Just prior to entering the pre-reformer, the raw feed-stock is mixed with superheated steam (Stream B8) and recycled fuel gas (Stream R2) to achieve a H_2O to carbon ratio in the feed gas of 2.5:1. In the reformer, all higher hydrocarbons are reduced to hydrogen and carbon monoxide. A portion of these reduced species form methane via the catalyzed methanation reaction. The water-gas shift reaction also takes place. There is a slight temperature increase across the reactor due to the exothermic methanation reactions.

FIGURE 1 LOGISTICS FUEL PLANT

Partially reforming the fuel removes higher chain hydrocarbons that would otherwise have the potential to produce carbon soot in the fuel cell. The partial reforming process also produces enough hydrogen and carbon monoxide to initiate the fuel cell reactions. Additional hydrogen for the fuel cell reaction will be produced by internally reforming methane within the fuel cell.

Reformed fuel gas exits the adiabatic pre-reformer at approximately 512°C (953°F) and 365 psia. A large amount of pre-reformer effluent, approximately 92 percent, is recycled in Stream S1. The recycled gas stream in S1 is split into two streams; S2 and R1. Stream S2 is cooled and eventually used, after cooling, drying, and processing in a PSA, to provide hydrogen to the hydrogenerator. Stream R1 is cooled to 490°C (915°F) in HX1 and mixed with superheated steam prior to being recycled back to the pre-reformer. The remaining fuel gas product from the pre-reformer in Stream F8 is depressurized through a throttle, or let-down, valve to 28 psia, mixed with CO-rich off-gas from the PSA in Stream S11, and routed to the fuel cell anode in Stream F9.

The fuel gas recycle in Stream S2 is cooled to 38°C (100°F) in a series of heat exchangers. Any condensate produced during cooling is removed and recycled to the bottoming cycle condenser after first passing through a sparger that is used to remove dissolved gases. The recycled dry fuel gas in Stream S7 is routed to a pressure swing adsorption (PSA) unit that selectively removes nearly pure hydrogen from the incoming recycled fuel gas. Hydrogen product from the PSA in Stream H1 is re-compressed to 700 psia and injected into the liquid raw feed stream. Hydrogen is added to the liquid logistic fuel at a rate of 0.5 Nm^3/kg of liquid logistic fuel feed (8 scf/lb of feed). The CO-rich fuel gas in Stream S8 is reheated in heat exchangers HX4 and HX1 to 346°C (654°F) and routed to the fuel cell in Stream S11.

Heat Recovery

The fuel conditioning system uses a series of seven heat exchangers to recover waste heat and to cool and regeneratively heat process streams. In the fuel conditioning system, there are six shell and tube type heat exchangers, labeled HX1 through HX6, and a fin-tube air cooler. Heat Exchangers HX1 through HX4 are used to regeneratively heat process streams while cooling recycled gas streams. Heat Exchangers HX5 and HX6 recover waste heat by heating boiler feed water. HX5 is used as an economizer and HX6 is used as a low pressure feed water heater. The air cooler rejects low temperature process heat to ambient.

Waste heat rejected by the fuel cell is recovered in either a shell and tube heat exchanger, labeled HX7, or in a heat recovery steam generator (HRSG). High temperature flue gas from the fuel cell's combustion stage in Stream E1 at 1,050°C (1,923°F) is split into two streams; Stream E2 is cooled in the HRSG while the other is routed to HX7 which is the process air heater. Heat Exchanger HX7 heats incoming ambient air from 42°C (107°F) to 720°C (1,328°F). The fuel cell cathode requires this high air temperature. The flue gas stream is cooled from 1,050°C (1,923°F) to 128°C (262°F). The cooled flue gas in Streams E3 and E4 are combined and routed to the flue gas chimney.

Prime Movers

Oxygen, supplied by an ambient air stream, is required by the fuel cell cathode to complete the fuel cell reaction. Ambient air in Stream A1 is minimally pressurized (16.5 psia) by an air blower. This pressure should be enough to overcome the total airside pressure drop. The pressurized air stream is then heated to 720°C (1,328°F) in Heat Exchanger HX7. The hot air stream is then sent to the fuel cell cathode. Most of the oxygen contained in the air stream participates in the fuel cell reaction. The balance of oxygen is used in post cell combustion reactions. Oxygen utilization by the fuel cell is approximately 71 percent. Overall oxygen utilization, including that required for post cell combustion, is approximately 76 percent.

Fuel Cell & DC to AC Conversion

High temperature air in Stream A3 and high temperature fuel gas in Stream F10 enter the fuel cell cathode and anode respectively. The water content of the fuel gas has been increased to 40 percent by the addition of superheated steam (Stream B9). The temperature of the fuel is approximately 416°C (780°F) and that of the air approximately 720°C (1,328°F). Hydrogen and carbon monoxide produced in the adiabatic reformer initiate the fuel cell reaction and produce dc electrical energy. Additional hydrogen is generated through internal reforming of methane. The endothermic reforming reaction helps keep air utilization values high and parasitic power requirements low by reducing the need to cool the fuel cell.

The plant operates at a cell voltage of 0.79 and produces 3,534 kWe of dc electrical energy. Overall hydrogen utilization in the fuel cell is 94 percent. After completion of the fuel cell reactions, the remaining fuel, consisting of unreformed methane and unconverted hydrogen and carbon monoxide, is mixed with the cathode exhaust and combusted. The heat of combustion is used to heat incoming air and to generate steam in downstream heat exchangers.

The inverter efficiency was assumed to be 96.5 percent in this case, which is consistent with existing technology.

Components can be sized once the state point information was determined. The sized components are then integrated to form the logistics plant as shown in Figure 1.

Cost Estimating

FETC has completed a cost estimate on a 4 MW logistics fueled power plant. The fuel system cost is estimated based upon 1997 dollars, plant size large enough to supply fuel to a 4 MW plant, and an Equity Return rate of 20 percent. Cost estimates of the logistics fuel processor yielded the following:

- Capital Cost - $2,351/kW
- Operating Cost - $4,766,000/year
- Cost of Electricity - $71.76/MW-hr

A previous cost estimate of a 4 MW gas turbine plant operating on natural gas showed the following cost data:

- Capital Cost - $1,306/kW
- Operating Cost - $739,000/year
- Cost of Electricity - $38.06/MWhr

A 4 MW advanced concept fuel cell/ gas turbine combined cycle unit, including the logistics fuel processor developing fuel gas for the plant, yields the following cost data:

- Capital Cost - $3,656/kW
- Operating Cost - $5,505,000/year
- Cost of Electricity - $109.82/MWhr

Acknowledgement

This work is a task of U.S. DOE CONTRACT DE-AM21-94MC31166. Parsons would like to thank the responsible FETC Program Manager Mr. Thomas George for his guidance and suggestions in all aspects of the Parsons fuel cell task. Thanks are also extended to FETC researchers David Berry and David Lyons for their help in defining the operating conditions of the logistics fuel processor, its integration with the advanced technology fuel cell candidate, and evolution of an advanced concept that promises to reduce fuel processor footprint and cost.

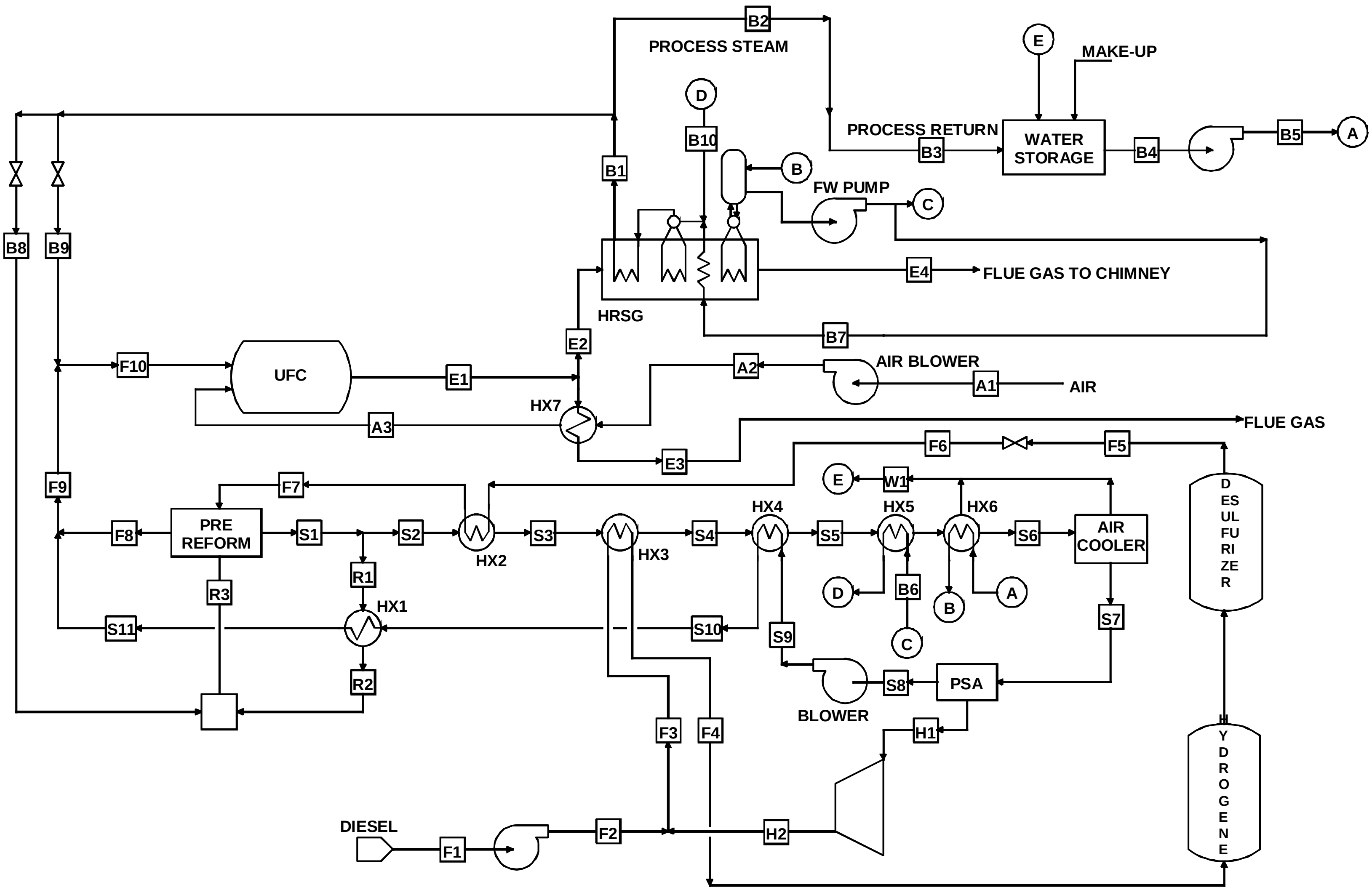

FIGURE 2 LOGISTIC FUELS PLANT DIAGRAM